



Serial No. N7196

NAFO SCR Doc. 21/028REV

SCIENTIFIC COUNCIL MEETING – JUNE 2021

Spatial-temporal variation in Greenland shark (*Somniosus microcephalus*) bycatch in the NAFO Regulatory Area

M.R. Simpson¹, L. Gullage¹, C. Konecny¹, N. Ollerhead¹, M. A. Treble², A. Nogueira³ and F. González-Costas⁴

¹Department of Fisheries and Oceans Canada, P.O. Box 5667, St. John's, NL, Canada A1C 5X1

²Department of Fisheries and Oceans Canada, Freshwater Institute, Winnipeg, Manitoba, Canada R3T 2N6

³Greenland Institute of Natural Resources, Box 570, 3900 Nuuk, Greenland

⁴Instituto Español de Oceanografía, Vigo, Spain

ABSTRACT

Spatial and temporal variation in Greenland shark (*Somniosus microcephalus*) bycatch occurrence was investigated using At-Sea Fisheries Observer data and MaxEnt, a maximum entropy species distribution model. Within the Northwest Atlantic Fisheries Organization Regulatory Area (NRA), the Flemish Pass, the slopes of the Flemish cap, and the shelf edge of Divisions 3NO contained areas of suitable habitat where Greenland shark bycatch is expected to occur. However, it should be noted that there are major areas of Greenland shark bycatch outside the NRA, in the Canadian and Greenland Exclusive Economic Zones (EEZ).

INTRODUCTION

Greenland shark (*Somniosus microcephalus*) bycatch in fisheries regulated by the Northwest Atlantic Fisheries Organization (NAFO) has been of concern to the Northwest Atlantic Fisheries Organization (NAFO) Fisheries Commission (FC) (NAFO/FC Doc. 16/11) for a number of years. Greenland sharks have an extremely conservative life history, with longevity estimated to be the highest documented for any vertebrate (392 ± 120 yrs) and therefore, bycatch is a concern (Nilsen et al., 2016). However, accurate estimates of fishing mortality are unavailable, because bycatch and subsequent discarding of Greenland sharks are not recorded in most catch statistics, except when At-Sea Observers (ASOs) are aboard commercial vessels. Also, there are uncertainties in the bycatch data that have been recorded, for example Greenland shark bycatch weight is difficult to estimate and numbers are often not available. In recent years a number of analyses have been conducted to provide NAFO Scientific Council (SC) with information on Greenland shark bycatch and discards in fisheries within the NAFO Regulatory Area (NRA) and adjacent Exclusive Economic Zones (EEZs) (Hendrickson, 2018; Hendrickson et al. 2018; Simpson et al. 2018; Hedeolm et al. 2018; Bryk et al. 2018; Wheeland and Devine 2018; Gonzalez-Costas and Ramillio 2019; Wheeland et al. 2019, and Gonzalez-Costas and Ramillio 2020).

In 2019 the NAFO FC requested the SC to identify areas and times where bycatch and discards of Greenland sharks have a higher rate of occurrence. Species distribution models (SDMs) are widely used for modelling species geographic distributions based on correlations between occurrence records, and environmental conditions. MaxEnt (maximum entropy), is a commonly used presence-only SDM that is able to account for the lack of absence data, which makes it a suitable candidate to model fisheries bycatch occurrence data. MaxEnt



uses a background sample randomly drawing from the study area to compare with the distribution of the presence data along the given environmental gradients. We apply this model to investigate the spatial distribution of Greenland shark bycatch, to gain insight into areas where bycatch occurs, and expand upon the point pattern distributions previously provided to SC (e.g., Simpson et al (2018)).

METHODS

Initially, Greenland shark occurrences were compiled for the NAFO Convention Area, from all available data sources, including both fisheries (Canadian ASO, NAFO ASO, Spanish Scientific Observers, Greenland fisheries logbooks) and DFO survey data (Figure 1). Previous analyses have indicated that bycatch in Subarea 0 occurs in both coastal areas, as well as deeper waters of the Davis Strait. In addition, it has been observed that bycatch Division 0A contains more juvenile Greenland sharks than the bycatch in more southern areas. Therefore, in order to assess spatial and temporal trends in the NAFO Regulatory Area (NRA) and adjacent areas within the Canadian EEZ a subset of the data containing only ASO data was selected for areas south of 61 degrees north latitude.

Spatial Analysis:

Greenland shark occurrences were compiled using a subset of data collected by ASOs from Newfoundland and Labrador (NL) (1983 – 2019), Spain (1999 – 2017), and the NAFO Secretariat (2014 – 2019). In total these datasets contained 7,325 observations of Greenland shark from 1983 – 2019, distributed throughout NAFO Divisions 2GHJ3KLMNOP (including the NRA and adjacent EEZs, Figure 2).

Environmental data layers chosen to support the delineation of Greenland shark bycatch included: (1) bathymetry and (2) monthly mean bottom temperature. Bathymetric data were taken from The General Bathymetric Chart of the Oceans (GEBCO), and were provided at 15 arc second resolution. Bottom temperature data was generated by the Bedford Institute of Oceanography North Atlantic Model (BNAM) as monthly means averaged over the 1990 – 2015 time period. This data was made available on the Government of Canada's Open Data Portal at a 1/12 degree spatial resolution.

Spatially replicated Greenland shark observations were removed so that only a single observation at any location was retained to remove redundancy. The study area was restricted to Subareas 2+3, but further restrictions to the boundary were also made in areas near the coastline where monthly mean bottom temperature was not available. To address this, a 30 km buffer was generated along the NL coastline. Each of the data layers were clipped to the study area (Figure 3) and environmental data were resampled to 1/12 degree to match the spatial resolution of the coarsest layer (monthly mean bottom temperature) to satisfy requirements for use in MaxEnt.

In order to increase model efficiency and quality (De Marco and Nóbrega 2018), environmental variables were assessed for collinearity using a calculation of variance inflation factor (VIF) available in the USDM package for R (Naimi et al. 2014, R Core Team 2020). Highly collinear variables were excluded through a stepwise process until remaining variables had a VIF < 10 (Dormann et al. 2012). Based on this analysis, bathymetry and only monthly mean bottom temperatures for March and November were retained for use with MaxEnt (Table 1). The final environmental layers are presented in Figure 4.

One of the key assumptions made by MaxEnt is that occurrence data is collected systematically throughout the study area (Phillips et al. 2009). However, like many real-world datasets, Greenland shark occurrences were collected in an opportunistic manner with observations biased towards heavier fished areas (Kramer-Schadt et al. 2013). To account for this, it is recommended that similar sampling bias be applied when selecting background points, which are used by MaxEnt in the modelling process. To accomplish this the Greenland shark occurrence data were interpolated using kernel density estimation (KDE) to generate a map of sampling bias throughout the study area from which biased background points could be selected (Figure 5).

MaxEnt was set up to run with default feature class and regularization settings to a maximum of 10,000 iterations. To account for sampling bias 10,000 background points were randomly selected from the interpolated sampling bias layer (Figure 5). In total, 50 sets of training and testing data were generated for the 4,136 Greenland shark observations. For each of the sets, 75% of the data (3,102) was used to train the model and 25% of the data (1,034) was used to test the model. A model was produced for each of the training/testing combinations, generating 50 individual Greenland shark bycatch models. These models were then averaged to generate a single model for the species (Figure 6). The standard deviation for the 50 models was also calculated (Figure 7).

The evaluate function from the Dismo package in R was used to calculate the maximum training sensitivity plus specificity threshold (0.323), which was used to transform the continuous bycatch prediction (Figure 6) to a binary score (Figure 8). This threshold represented the value at which the sum of the sensitivity (true positive rate) and specificity (true negative rate) was the highest (Hijmans et al. 2020).

Of the three environmental variables used to develop the model, bathymetry was consistently identified as the most important contributor when determining the occurrence of Greenland shark bycatch. The mean suitability of the testing dataset ($n = 1,034$) was 0.67, while the mean suitability of randomly generated background points ($n = 10,000$) was 0.18, providing initial indications that the model was able to delineate between higher and lower bycatch levels. A number of additional evaluation metrics were also calculated (Table 2) to support this evaluation.

Area Under the Receiver Operating Characteristic Curve (AUC) for this model was found to be 0.915 (Table 2). AUC, which ranges from 0 to 1, is one of the most commonly reported metrics for MaxEnt models, measuring the ability of a model to correctly classify species distribution over a continuous range of threshold values (Pearce and Ferrier 2000). In general, an AUC value of 0.5 suggests a model that is unable to perform better than random, while models with AUC values >0.7 are considered to be good (Pearce and Ferrier 2000). However, because there have been a number of concerns associated with the use of AUC for assessing performance of SDMs (Lobo et al. 2007), additional evaluation metrics were also calculated.

The continuous Boyce index uses presence data to measure how much model predictions differ from random distributions of the observed presences across the prediction gradients (Boyce et al. 2002). This is accomplished by binning the bycatch map and determining the predicted versus the expected occurrence frequencies within each bin. A predicted/expected (P/E) ratio is calculated for each bin and a Spearman rank is used to determine if the ratio increases with bycatch. If the model is performing well, the low bycatch bins contain fewer occurrences than is expected by chance, and higher bycatch bins have more occurrences than expected by chance. The Boyce Index ranges from -1 to +1, with positive values suggesting the model is performing better than random and negative values suggesting the model is performing worse than random (Hirzel et al. 2006). The Boyce Index calculated for the Greenland shark model was 0.950 (Table 2).

Another commonly used metric for evaluating SDMs is the True Skill Statistic (TSS), which relies on a confusion matrix (Table 2) to assess accuracy by comparing the number of correct classifications (True Positivity Rate and True Negativity Rate) with the number of incorrect classifications (False Positivity Rate and False Negativity Rate) to determine model sensitivity and specificity.

$$TSS = Sensitivity + Specificity - 1$$

Like the Boyce Index, this metric also ranges from -1 to +1, with values ≤ 0 suggesting performance no better than random and values >0 suggesting better model performance (Allouche et al. 2006). For the purpose of this exercise, TSS was calculated for the binary model defined using the maximum training sensitivity plus specificity threshold (0.406) (Figure 7) and was found to be 0.773 (Table 2).

Temporal Analysis:

The frequency of occurrence of observed Greenland shark bycatch from Canadian ASOs was compared to frequency of occurrence of all Canadian fishing effort in the NRA by month and quarter (Fig. 9).

RESULTS & DISCUSSION

Greenland shark bycatch is widespread, extending from NAFO Divisions 0A and 1A south to 5Z. Available data indicates Greenland shark bycatch predominately occurs within the Canadian and Greenland EEZs. It must be reiterated that patterns in the occurrence of Greenland shark bycatch presented in this paper depended on the type of fisheries being conducted (i.e., fishing area/directed species/gear type), and the level of ASO coverage of those fisheries. Given that Greenland shark bycatch and subsequent discarding in unobserved fisheries are not recorded in catch statistics, complete representation of bycatch distribution and estimates of total fishing mortality are unavailable.

This paper focused on the distribution of Greenland shark bycatch in Subareas 2+3, with a particular focus on the NRA. Of the three environmental variables used in the final model, bathymetry was consistently identified as the most important contributor when determining areas of bycatch for Greenland shark, while monthly mean bottom temperatures for March and November were less important.

The model indicates that Greenland shark bycatch is greatest in the deeper waters along the shelf edge in Divisions 3OP, and the area of the Laurentian channel. Bycatch is also associated with the edge of the Labrador shelf and the Grand Banks and deeper areas such as the Hawke channel, Funk Island Deep and the slopes of Saglek, Nain, and Hamilton Banks. Within the NRA, Greenland shark bycatch occurs within the Flemish Pass, along the slope of the Flemish Cap and along the shelf edge in Divisions 3NO. Greenland shark bycatch does not appear to be associated with the shallower waters of the Flemish Cap or the Grand Banks. The model also indicated that the shelf edge in NAFO divisions 3OP, in the area of the Laurentian channel is also an area with high bycatch of Greenland shark.

The occurrence of Greenland shark bycatch is higher than the proportional effort in fishing during December to March, for the Canadian fleets fishing in the NRA. Similarly, in August and September, there is a relatively large proportion of sets with Greenland shark bycatch while there is proportionally little fishing effort.

While the results of this analysis suggest spatial or temporal fishing closures might be considered by managers it is important to keep in mind that the model is based only on those fisheries that had an ASO collect data. Therefore, the data is considered biased or incomplete and it is difficult to make definitive conclusions on the location of high occurrence of bycatch. Alternative management procedures, such as live release and care in handling (e.g. taking care not to lift sharks by their tail when returning them to the water); gear modifications (e.g., otter trawl excluder devices, longline circle hooks instead of J hooks, reduced longline gangion breaking strength, increased gillnet tensioning, magnetic or chemical repellents), shark bycatch limits (e.g., reduced bycatch-to-target species ratio, illegal possession/landings/sales of particular shark species); or reductions in fishing effort (e.g., shortening durations for trawling, reducing soak times for gillnets and longlines, reducing the number of gillnets or longline hooks, restricting the number and size of vessels allowed in a fishery) may also provide increased protection to Greenland sharks.

ACKNOWLEDGEMENTS

The authors thank Carol Ann Peters, Heath Stone, Joanne Gauthier, and Dr. Heather Bowlby for providing data from the regional DFO At-Sea Fisheries Observer Programs and/or DFO regional research vessel survey programs, as well as Canadian At-Sea Observers who collected data aboard commercial vessels under adverse conditions. We are also grateful to Fisheries and Oceans Canada staff who participated in Canadian research surveys.

REFERENCES

- Allouche, O., Tsoar, A., and Kadmon, R. 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, 43:1223-1232.
- Boyce, M.S., P.R. Vernier, Nielsen, S.E., and Schmiegelow, F.K.A. 2002. Evaluating resource selection functions. *Ecol. Model.*, 157:281-300.

- Bryk, J.L. K.J. Hedges and M.A. Treble. 2018. Summary of Greenland shark (*Somniosus microcephalus*) catch in Greenland halibut (*Reinhardtius hippoglossoides*) fisheries and scientific surveys conducted in NAFO Subarea 0. NAFO SCR Doc. 18/041.
- De Marco, P.J. and Nóbrega, C.C. 2018. Evaluating collinearity effects on species distribution models: An approach based on virtual species simulation. PLoS ONE 13(9): e0202403. <https://doi.org/10.1371/journal.pone.0202403>
- Dormann, C.F. et al. 2012. Collinearity: A review of methods to Deal with it and a simulation study evaluating their performance. Ecography, 35:1-20.
- González-Costas, F. and G. Ramilo. 2019. Greenland sharks (*Somniosus microcephalus*) Spanish data (Surveys and Fishery) in NAFO Regulatory Area. NAFO SCR Doc. 19/030.
- Hedeholm, Rasmus, R. Nygaard and A. Nogueira. 2018. Greenland shark in Greenland waters in NAFO Subarea 1 and ICES XIV. NAFO SCR Doc. 18/037.
- Hendrickson, L. 2018. Greenland shark (*Somniosus microcephalus*) catches off the U.S. East Coast based on data from data from research surveys, fishery observer programs, logbooks and tagging programs conducted by the U.S. National Marine Fisheries Service. NAFO SCR Doc. 18/016.
- Hendrickson, L. Jana Aker, Sebastian Glindtvaad and Tom Blasdale. 2018. Greenland shark (*Somniosus microcephalus*) catches in fisheries conducted in the Northwest Atlantic Fisheries Organization Regulatory Area. NAFO SCR Doc. 18/020REV2.
- Hijmans, R.J., Phillips, S., Leathwick, J., and Elith, J. 2020. Dismo: Species Distribution Modeling. R package version 1.3-3. <https://CRAN.R-project.org/package=dismo>
- Hirzel, A.H., Le Lay, G., Helfer, V., Randin, C., and Guisan, A. 2006. Evaluating the ability of habitat suitability models to predict species presences. Ecol. Model., 199:142-152.
- Kramer-Schadt et al. 2013. The importance of correcting for sampling bias in MaxEnt species distribution models. Biodiversity Research, 19:1366-1379.
- Lobo, J.M., Jiménez-Valverde, A., and Real, R. 2007. AUC: a misleading measure of the performance of predictive distribution models. Global Ecology and Biogeography, 17:145-151.
- Naimi, B., Hamm, N.A.S., Groen, T.A., Skidmore, A.K., and Toxopeus, A.G. 2014. Where is positional uncertainty a problem for species distribution modelling? Ecography, 37 (2): 191-203.
- Nielsen, J., R. B. Hedeholm, J. Heinemeier, P. G. Bushnell, J. S. Christiansen, J. Olsen, C. B. Ramsey, R. W. Brill, M. Simon, K. F. Steffensen, J. F. Steffensen. 2016. Eye lens radiocarbon reveals centuries of longevity in the Greenland shark (*Somniosus microcephalus*). Science 353 (6300):702-704.
- Pearce, J. and Ferrier, S. 2000. Evaluating the predictive performance of habitat models developed using logistic regression. Ecological Modelling, 133:225-245.
- Phillips, S.J., Dudik, M., Elith, J., Graham, C.H., Lehmann, A., Leathwick, J., et al. 2009. Sample selection bias and presence-only distribution models: Implications for background and pseudo-absence data. Ecological Applications, 19: 181-197.
- R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Simpson, M.R., C.M. Miri, and R.K. Collins. 2018. Distribution and Analysis of Canadian Greenland shark (*Somniosus microcephalus*) bycatch in the NAFO Regulatory Area. NAFO SCR Doc. 18/026.
- Wheeland, L. and B. Devine. 2018. Bycatch of Greenland shark (*Somniosus microcephalus*) from inshore exploratory fisheries adjacent to NAFO Division 0. NAFO SCR Doc. 18/044.
- Wheeland, L., M. Treble, A. Nogueira. 2019. Overview of sources of uncertainty in reported catches of Greenland shark *Somniosus microcephalus* within the NAFO Convention Area.

Table 1. Retained environmental variables and associated Variance Inflation Factors (VIF).

Environmental Variable	Variance Inflation Factor (VIF)
Bathymetry	1.11
Bottom Temperature (March)	8.38
Bottom Temperature (November)	8.20

Table 2. Evaluation metrics used to assess overall model performance.

Evaluation Metric	Result
Mean Suitability of Test Data	0.67
Mean Suitability of Background Data	0.18
AUC	0.915
Continuous Boyce Index	0.95
True Skill Statistic (TSS)	0.773
Confusion Matrix	
98699 (True Positive)	48 (False Negative)
1810 (False Positive)	8190 (True Negative)
Sensitivity	0.954
Specificity	0.819

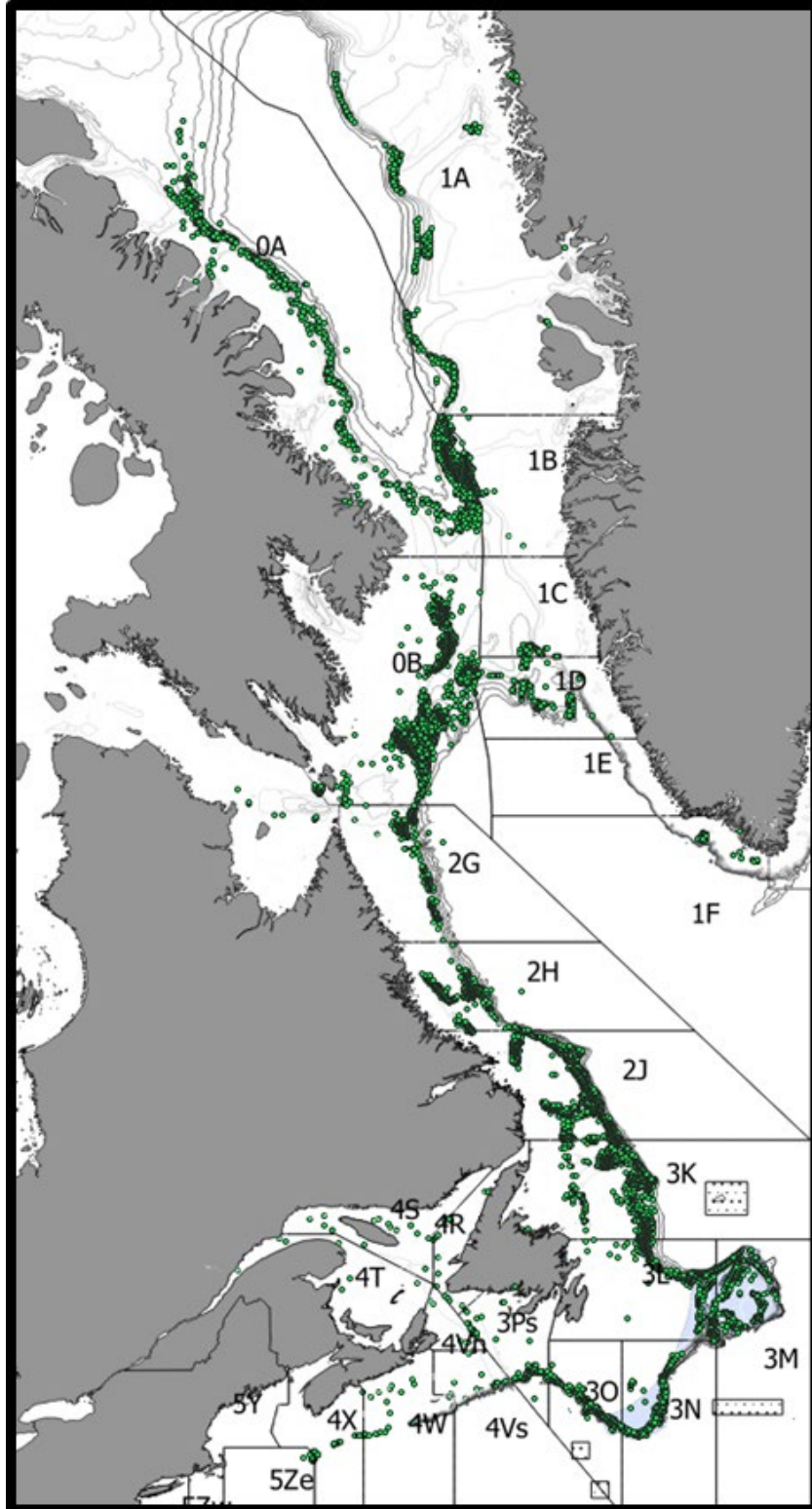


Figure 1. Occurrence of Greenland shark bycatch from all available data sources.

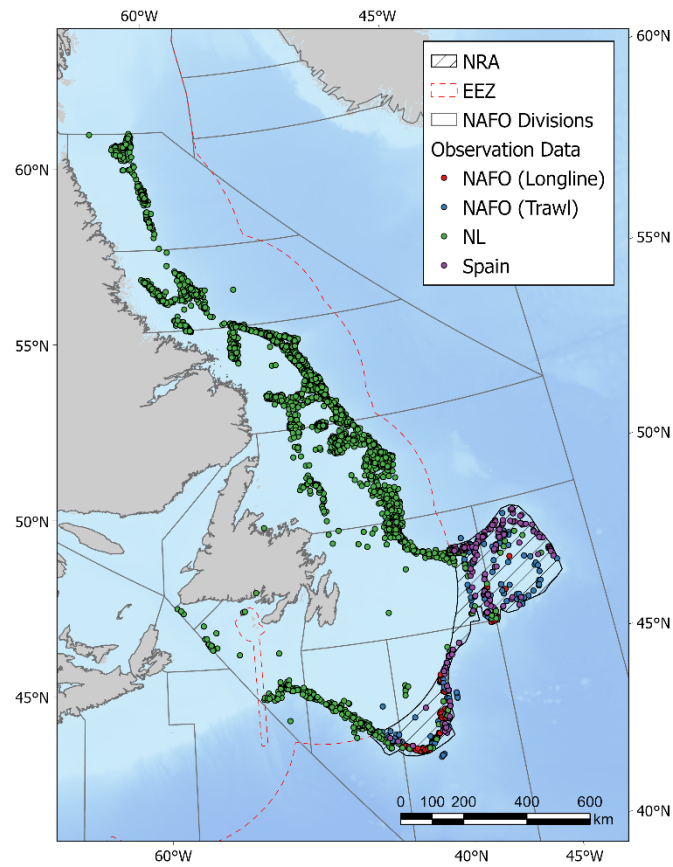


Figure 2. Greenland shark occurrences used in the MaxEnt model.

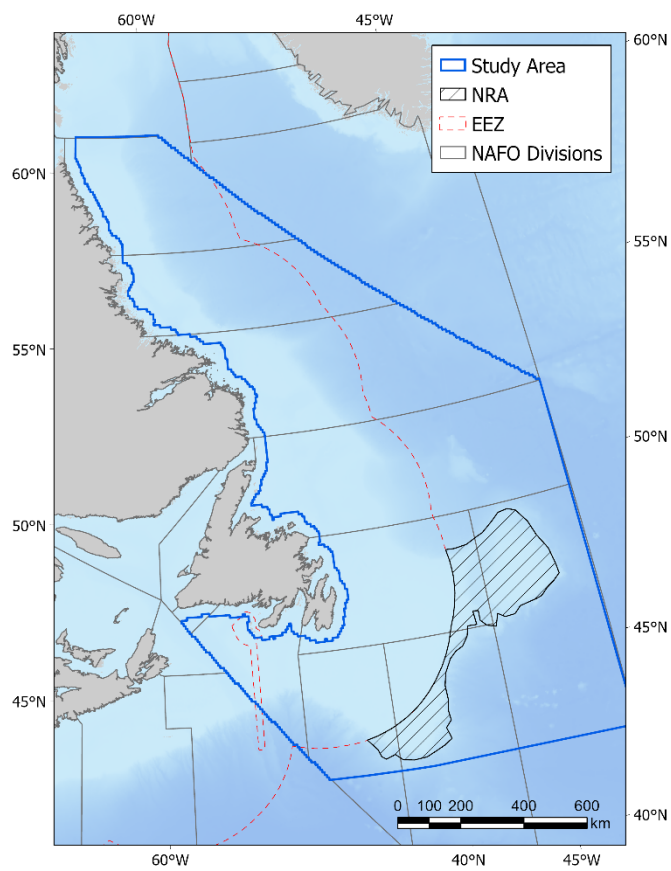


Figure 3. Extent of the study area used to model Greenland shark bycatch distribution.

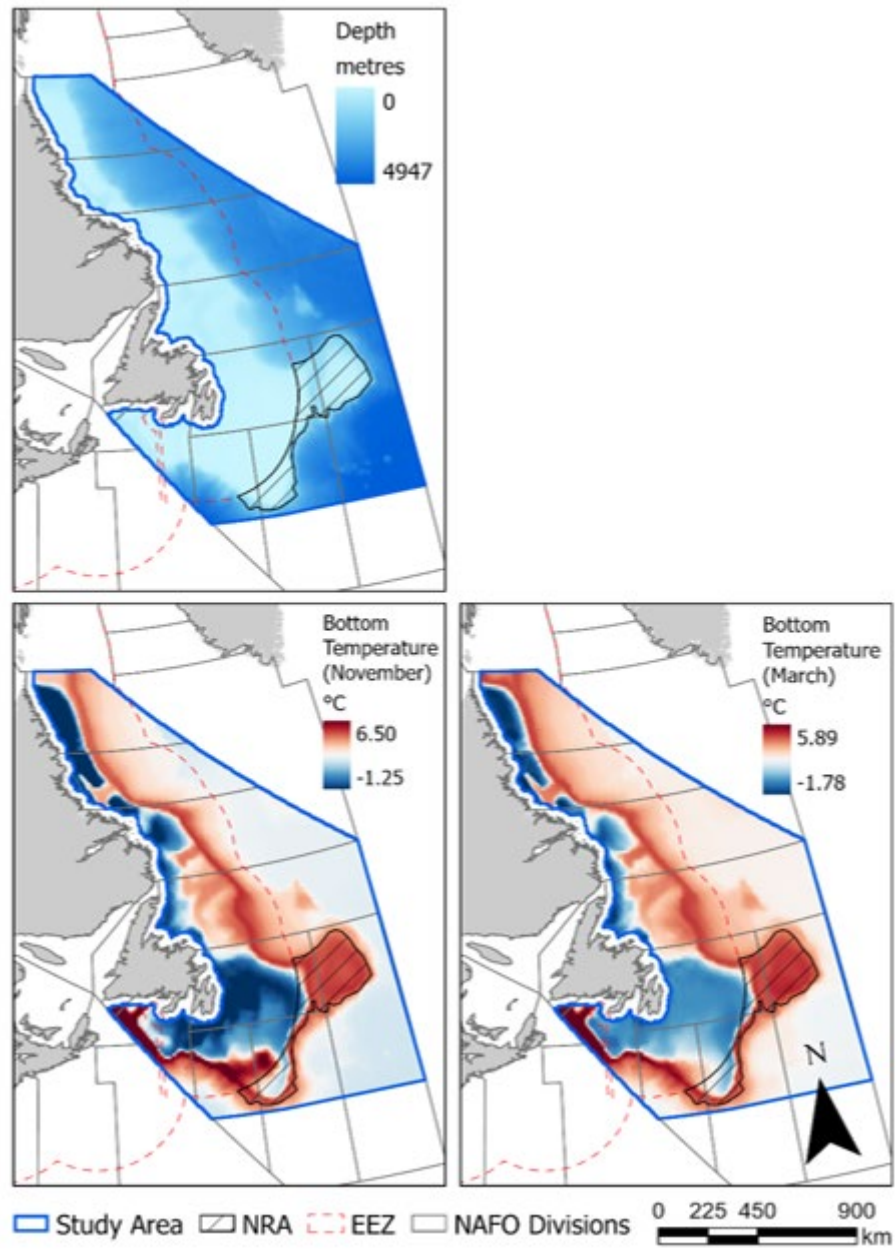


Figure 4. Environmental variables retained for use in modelling exercise.

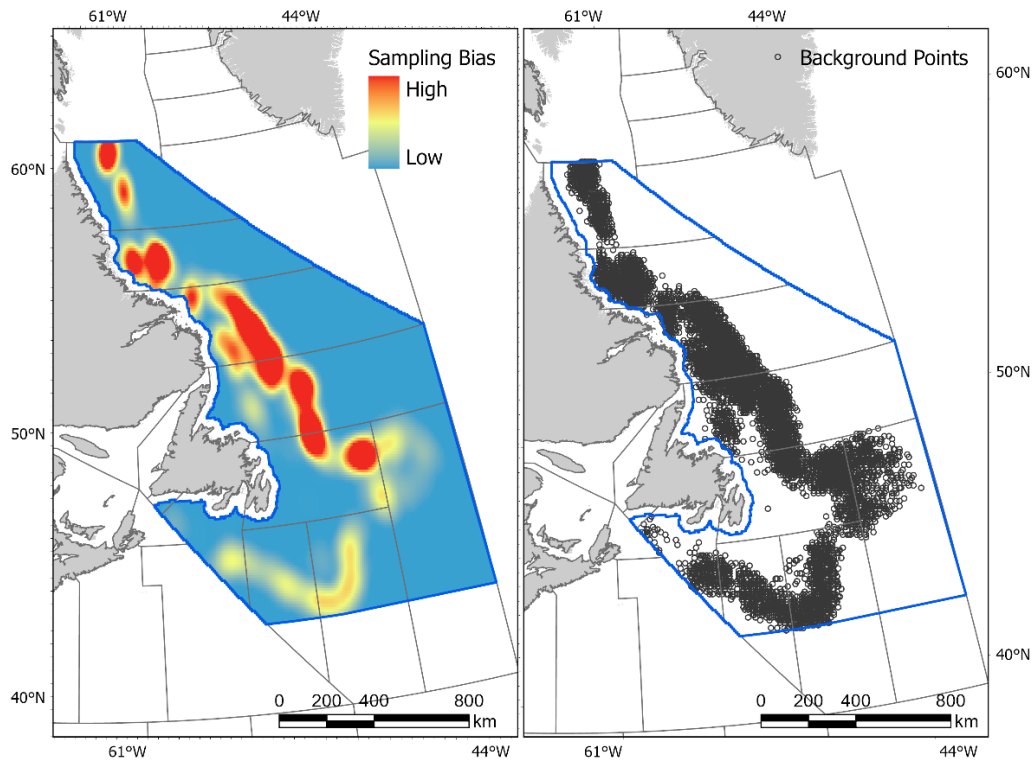


Figure 5. Kernel Density Estimation (KDE) of Greenland shark occurrence data used to simulate sampling bias (left) and the associated biased background points selected for use in MaxEnt (right).

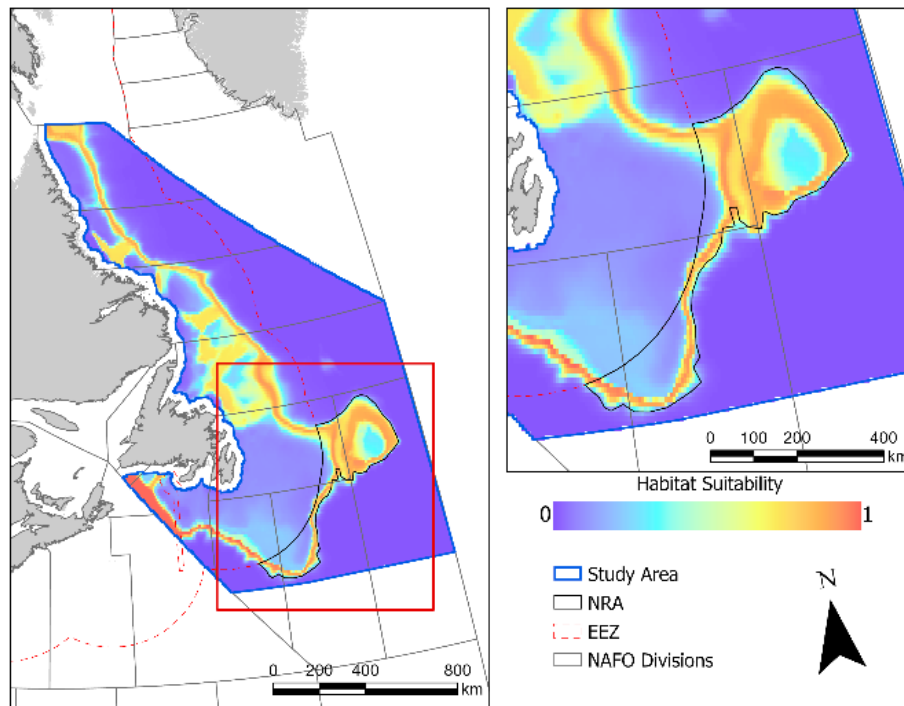


Figure 6. Mean bycatch model for Greenland shark.

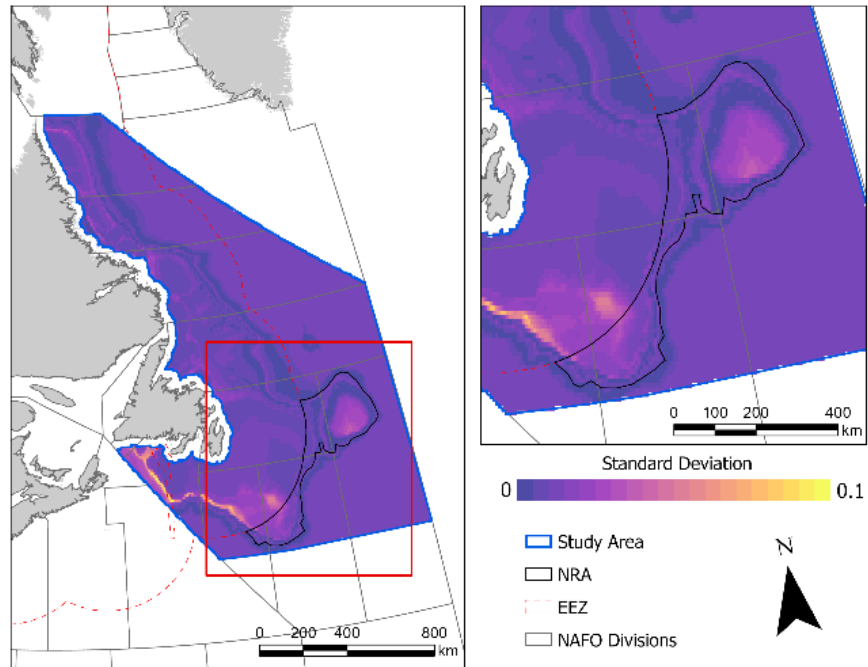


Figure 7. Standard deviation of bycatch models ($n = 50$) for Greenland shark.

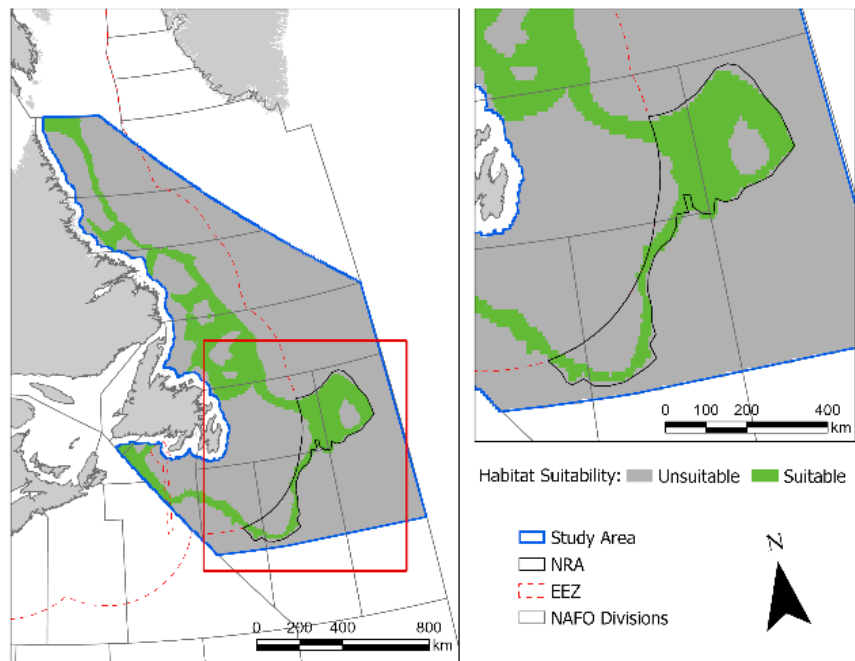


Figure 8. Binary bycatch model for Greenland shark based on maximum training sensitivity plus specificity threshold (0.323).

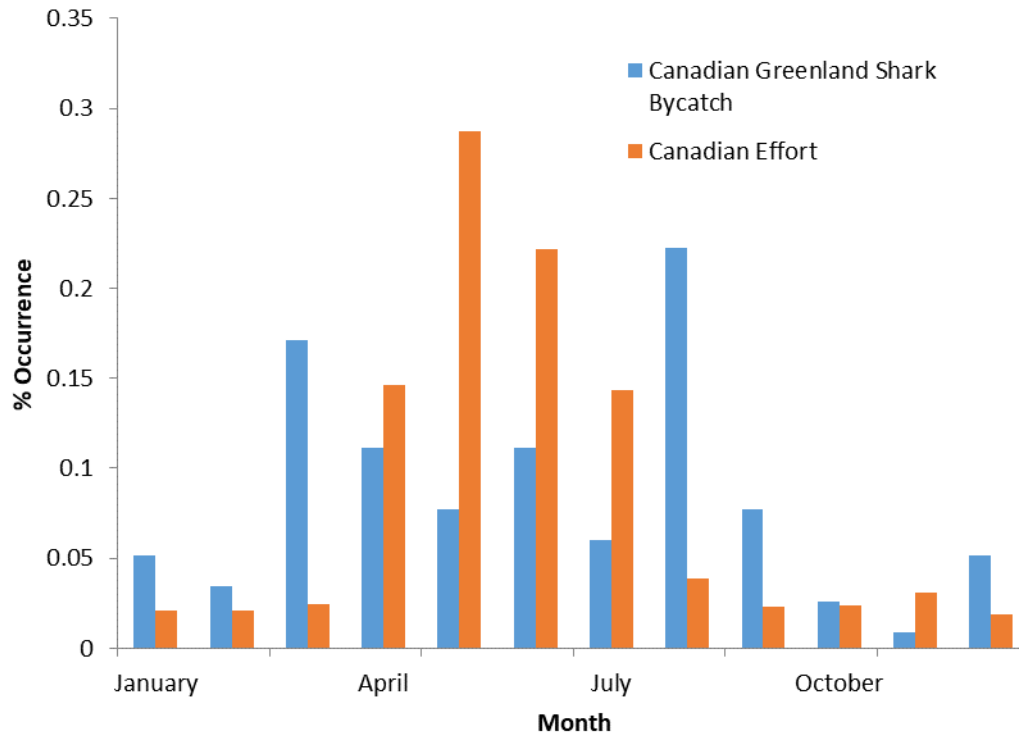


Figure 9. Percent occurrence of Canadian Greenland shark bycatch and overall fishing trips in the NRA by month (January-December).